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Neuroprosthetics

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Introduction

Neuroprostheses are electronic human-computer interfaces that function to replace or enhance specific aspects of the central nervous system. There are two main types of neuroprosthetics currently in use today: motor and sensory. Technological advances have made possible a wide variety of prosthetic devices that have greatly enhanced the quality of life of many patients who have lost sensory or motor functions.

Sensory neuroprosthetics

There has been a wide interest in neuroprosthetics that replace primary sensory organs. Perhaps the oldest and most successful example of a sensory neuroprosthetic is the cochlear implant. While not a perfect replacement, it has had a tremendous impact in restoring basic auditory function to patients. Research is also underway to develop a visual prosthetic device. However, limitations in current technology and our understanding of the visual pathway present roadblocks in the development of an adequate device.

Seminal work in developing an auditory prosthesis was conducted by French researchers in 1957, and involved stimulation of the auditory nerve with a single channel electrode.¹ Even with this simple setup, the patient was able to distinguish monosyllabic words. More recent technologies informed by our understanding of the auditory system have dramatically improved this performance. For example, the portion of the auditory nerve that runs inside the organ of Corti is tonotopically organized; tones are spatially arranged by frequency. Cochlear implants take advantage of this by breaking incoming sound up into multiple frequency channels. Each channel is fed along its own electrode to the corresponding portion of the auditory nerve replicating the natural function of the cochlea. Just four frequency channels are sufficient to understand speech, which is remarkable considering that roughly 30,000 hair follicles normally stimulate the nerve.¹

Current implants have up to 22 channels, more than adequate for understanding speech, but still inadequate for auditory tasks such as music perception.² A 2001 study in *Nature* demonstrated that improvements in music perception will require improvements in sound encoding.³ Not only does the auditory system decompose sound by frequency, it also separates sound into two components: a slowly varying frequency envelope suitable for speech recognition, and a rapidly varying fine structure used in pitch perception and sound localization.

The development of a visual prosthetic has been much more difficult. Firstly, the amount of visual informa-

tion entering the eyes is more complicated and dense compared to the auditory system. While four frequency channels were adequate for functional hearing, having only four discriminate regions for vision is inconceivable. Researchers have suggested that a 10x10 array of pixels can restore just enough vision for navigation and object avoidance,⁴ while as many as 1000 pixels are need to restore face recognition and reading.⁵ The retina is also an incredibly compact organ with a receptor cell density that cannot be easily replicated. One group demonstrated that a silicon microarray for nerve stimulation can be machined with electrodes that are 0.4mm apart, although this is still a far cry from the maximal cone density found in the fovea.⁶

Despite the technological challenges of creating an artificial replacement retina, it still remains the primary site of visual prosthetic research for a number of reasons. Firstly, just as the cochlea is tonotopically organized, the retina has a natural spatial organization which simplifies prosthesis design. Secondly, a retinal approach takes advantage of natural visual processing that begins at that level, including colour perception and edge accentuation.⁷

Motor neuroprosthetics

Perhaps the most well known type of motor neuroprosthetic is the artificial cardiac pacemaker. Cardiac pacemakers are devices implanted in the muscular wall of the heart as a replacement for the sinoatrial node, which is required to maintain the sinus rhythm of the heart.⁸ Another example of an autonomic neuroprosthetic device is the bladder control prosthesis used in patients with spinal cord injuries. Although still in the experimental stage, neuroprosthetic devices implanted at various areas of the urinary tract attempt to replicate the original function of the urinary tract. Controlled by an external transmitter, the device is implanted at the sacral anterior root ganglia of the spinal cord. Signals sent from the device assist in bladder control, defecation and achieving and sustaining full erections in male patients.⁹

In addition to autonomic devices, there are numerous motor prosthetics under development. The neuroprosthetic device showing the most promise for motor control is an implantable computer chip called the Brain-Computer Interface (BCI). The BCI can be implanted into the grey matter of the brain, the skull or outside the skull. The BCI collects distinct EEG patterns generated by the patient when they imagine specific movements of paralyzed body parts and converts them into signals controlling prosthetic devices.¹⁰ The BCI essentially translates the intentions of the user into movement of the prosthetic device.¹¹ Figure 1 shows an example of a brain-computer interface currently in clinical trials.

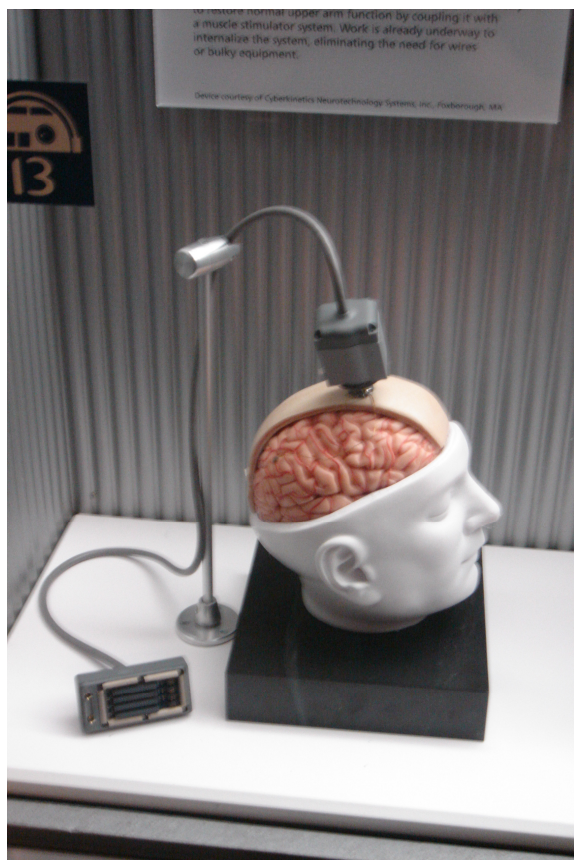


Figure 1. An example of a brain-computer interface.

Conclusions

In addition to the sensory and motor neuroprosthetics that have been discussed above, there is a new area of research focusing on cognitive neuroprosthetics. These devices aim to restore cognitive function to those who have suffered brain injury or paralysis due to trauma and those suffering from Alzheimer's disease and Parkinson's disease. Damaged brain tissue can be replaced by integrated circuits, which would help process information that would normally be done in the diseased region of the brain.¹²

Despite some difficult challenges in designing neuroprosthetic devices, such as the size of the device, power source and material interactions with human physiology, the work done thus far suggests a promising future.

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